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Effects of climate change on the future distributions of the top five freshwater invasive plants in South Africa

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ABSTRACT

A recent study shows that most aquatic alien plants in temperate cold climate are of tropical and subtropical origins and only those that can withstand cold climates become invasive. This suggests that a changing climate that becomes warmer may result in currently non-invasive alien plants becoming invasive in the future. To facilitate pre-emptive actions when controlling invasive aquatic plants in South Africa under climate change, we reconstructed predictive models for the five most damaging aquatic alien plants of freshwater systems in the country. We found evidence of contrasting shifts in species distribution ranges: the ranges of *Myriophyllum aquaticum* and *Pistia stratiotes* will contract, while *Azolla filiculoides*, *Eichhornia crassipes*, and *Salvinia molesta* will increase their future ranges with most suitable habitats found in the Western Cape province and along coastal areas. In addition, the predicted range contraction and expansion would result in some dams currently vulnerable to invasion becoming resilient while others that are currently resilient may become vulnerable due to climate change. These results can be used to develop future monitoring programs for aquatic ecosystems, prioritize control efforts, and raise public awareness on risks posed by these aquatic invasive plants, especially under future climate scenarios.

1. Introduction

Plants are moved around the globe into non-native areas to satisfy human needs. Of these non-native species, those that successfully spread beyond the point of introduction pose negative ecological and economic challenges (Mooney and Hobbs, 2000; Van Wilgen et al., 2001; Pimentel et al., 2005; McGeoch et al., 2010). These challenges are expected to be aggravated in the future as climate change is predicted to facilitate further spread of these species (Coetzee et al., 2009; Willis et al., 2010). Compared to terrestrial plants, aquatic plants are shown to have a higher probability of becoming invasive in new environments (see Andreu and Vilà, 2010) and, therefore, deserve perhaps more urgent attention (Padilla and Williams, 2004; Andreu and Vilà, 2010; Azan et al., 2015). Furthermore, ornamental pond industries and aquarium trade have been singled out as a strong contributing pathway to the introduction and spread of aquatic invasive plants (Kay and Hoyle, 2001; Henderson and Cilliers, 2002; Padilla and Williams, 2004; Madeira et al., 2007; Martin and Coetzee, 2011; Strecker et al., 2011; Azan et al., 2015).

In their recent study, Azan et al. (2015) showed that most plants traded in Canadian aquaria are of tropical and subtropical origins and that only those that can withstand cold climates become invasive. This finding suggests that if the Canadian climate becomes warmer in the future under climate change scenarios, even aquarium plants that are not currently invasive would likely become invasive (Verlinden et al., 2014). In this regard, reconstructing ecological niche models of alien plants under climate change becomes important in the sense that these models may assist in identifying (i) plants that might expand their geographic ranges while tracking favorable climates as well as (ii) areas likely to be invaded due to climate change.

In South Africa's freshwater systems, the top five most damaging alien plants, generally termed the “bad five” (Henderson and Cilliers, 2002), are of South American origin. This top five includes water hyacinth (*Eichhornia crassipes* (Mart.) Solms), water lettuce (*Pistia stratiotes* L.), parrot's feather (*Myriophyllum aquaticum* (Vell.) Verdc.), Kariba weed (*Salvinia molesta* D.S. Mitch.), and red water fern (*Azolla filiculoides* Lam.) (Van Wilgen et al., 2001; Hill, 2003; Richardson and Van Wilgen, 2004). Based on DNA barcoding, Hoveka et al. (2016) revealed that some prohibited aquatic alien plants are already in circulation in South Africa's aquarium trade. There is therefore an urgent need to strictly regulate this trade and design pre-emptive actions that take into account the behavior of alien plants in response to climate change.

In this study, we reconstruct predictive models of species ecological niches to identify how the “bad five” aquatic plants are likely to

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re-adjust their geographic ranges in response to future climate change. We also identify South Africa's dams located in areas climatically favorable for a range expansion of the "bad five" aquatic plants.

2. Materials and methods

2.1. Study species

In total, 21 aquatic weeds have been documented to be present in freshwater systems of South Africa (Henderson and Cilliers, 2002). Our focus in this study is on the five most damaging alien plants of South Africa's freshwater systems referred to as "bad five": *A. filiculoides*, *E. crassipes, M. aquaticum*, *P. stratiotes*, and *S. molesta*.

2.2. Species occurrence data

Distribution data for the "bad five" invaders were sourced from the National Herbarium Pretoria Computerized Information System (PRECIS) and the South African National Biodiversity Institute (SANBI)'s Integrated Biodiversity Information System (SIBIS). After removing duplicate records or doubtful point data, a total of 711 geographic points were obtained for *A. filiculoides*, 649 for *E. crassipes*, 180 for *M. aquaticum*, 129 for *P. stratiotes*, and 166 for *S. molesta*.

2.3. Climate data

Nineteen raster-based bioclimatic parameters for both current and future climate scenarios were used for ecological niche modeling (see supplementary Table S1). Spatially downscaled estimates of future climate for the year 2080 were obtained from the WorldClim database (http://www.worldclim.org/; Hijmans et al., 2005) at a spatial resolution of 2.5 arc minutes using the Commonwealth Scientific and Industrial Research Organization CSIRO-Mk3.0 GCM and the Special Report on Emissions Scenarios SRES A1B carbon emission scenario. Environmental variables were interpolated onto ArcGIS grids to ensure that all spatial data have the same geographic bounds and cell size as the study region.

2.4. Species distribution modeling

We used MaxEnt version 3.3.3 K (Phillips et al., 2006) to generate predictive models for current and future distribution (maps of climate suitability) of the "bad five" aquatic invaders. Although spatial autocorrelation is an issue of concern in most species distribution models, methods on how to correct or test for correlation between climatic variables are still not standardized (Lennon, 2002; Dormann, 2007). Notwithstanding, we tested for spatial autocorrelation in all environmental variables to address the issue of multicollinearity (Pearson correlation coefficient, $r < \pm\ 0.75$; supplementary Table S2). Variables that showed correlation strength above this range were excluded from the analysis. Additionally, we used jackknife statistics to evaluate the relative contribution of each of the 19 predictor variables to the models using the area under the curve (AUC) score (Pearson et al., 2007) (Figs. S1 and S2). An AUC value of 0.5 indicates that model prediction is not different from random, a value of 0.5–0.7 indicates poor performance, 0.7–0.9 indicates acceptable performance, and AUC >0.9 indicates high performance (Peterson et al., 2011). Based on the AUC score, the best predictor variables were identified. We then re-ran all models using only the best predictor variables, assigning 75% of the occurrence data for model training and the remaining 25% for model testing. To measure the variability in the model performance, 15 subsampling replicates were run for each model, and the default iteration parameter was changed to 5 000, which is sufficiently large to ensure model convergence. We employed the 10th percentile training presence threshold in order to generate prediction probability maps (Phillips and Dudik, 2008). Our model outputs followed a logistic distribution, with values ranging from 0 (indicating areas that are climatically unsuitable) to 1 (indicating areas that are climatically suitable) for species persistence.

2.5. Determination of habitat suitability

Output projections from MaxEnt for both current and predicted future climate parameters were converted from ASCII to Raster float using the ArcGIS software (ESRI ArcGIS version 10). Changes in geographical ranges of each species between current and future climate were calculated using the Spatial Analyst tools in ArcGIS (O'Donnell et al., 2012). Using the Zonal Statistics extension, we calculated the differences in projected shifts in climatic extent (estimated as the number of pixels gained or lost) such that species with an increased probability of occurrence under future climate projections were assigned a positive value (i.e., range expansion), whereas species with a decreased probability of occurrence under future projections were assigned a negative value (i.e., range contraction). The numbers of pixels gained or lost were then converted to surface area (km^2).

2.6. Fresh water system data

We retrieved from the South African Department of Water Affairs database (http://www.dwaf.gov.za) the shape files of all South Africa's dams. These shape files were then imported into ArcGIS and overlaid onto both maps of current and future climate suitability of all five species studied. This allows us to identify the dams that are located in areas climatically favorable for range expansion of these species.

3. Results

The minimum and maximum AUC values from model outputs generated by MaxEnt ranged from 0.832 to 0.916, with an average AUC value of 0.874. These results indicate a relatively high performance of our species distribution model. The current climate suitability maps for the "bad five" invaders are presented in Fig. 1. Areas that are climatically suitable (areas in red in Fig. 1) for the distribution of *A. filiculoides* are found in six of the nine provinces of South Africa, including the North West, Gauteng, Mpumalanga, Free State, Eastern Cape, and Western Cape provinces (Fig. 1a). However, *E. crassipes* has suitable climatic conditions in all nine provinces (Fig. 1b). In addition, areas suitable for the distribution of *M. aquaticum* are found in seven provinces including the Limpopo, North West, Gauteng, Mpumalanga, Eastern Cape, KwaZulu Natal, and Western Cape provinces (Fig. 1c). Lastly, for *P. stratiotes* and *S. molesta*, climatically suitable areas are found in the Limpopo, Mpumalanga, KwaZulu Natal, Eastern Cape, and Western Cape Provinces (Fig. 1d, e).

Of the 612 dams found in South Africa, 234 (38%) occur in areas that are currently climatically suitable for the establishment of at least one of the "bad five" invaders (Table 1). Of these, the highest number of vulnerable dams is located in the Western Cape province and the lowest number in the Northern Cape province (Table 1).

When the current distribution of the "bad five" invaders was projected into the future (year 2080), our model suggests that the distribution of the majority of the "bad five" plants is likely to expand except for two species. In particular, the range of *A. filiculoides* in the future will increase by 249912 km^2 (~1% of the currently suitable area; Table 2). The Limpopo and Northern Cape provinces, which are currently unsuitable (areas in blue) for *A. filiculoides,* will become suitable in the future (Fig. 2a). Similarly, for *E. crassipes*, its geographic range is predicted to expand by 471477.5 km^2 (~1.5% of the current suitable area; Fig. 2b). In contrast to this range expansion, the ranges of *M. aquaticum* and *P. stratiotes* are predicted to contract in the future by 2,113,839 km^2 (~9% of the current ranges) and 199,582.5 km^2 (~10% of the current potential suitable area), respectively (Fig. 2c, d). Although at the country scale, there was an overall range contraction for these two species, their ranges will locally expand mostly towards the